The University of Chicago

ELECTROSTATIC DEFLECTION STUDIES OF ALPHA-PARTICLES; THE ALPHAS FROM $Li^6(p,\alpha)He^3$

A DISSERTATION SUBMITTED TO THE FACULTY OF THE DIVISION OF THE PHYSICAL SCIENCES IN CANDIDACY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF PHYSICS

1940

BY

LEONARD C. MILLER

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Electrostatic Deflection Studies of Alpha-Particles; the Alphas from $Li^6(p,\alpha)He^3$

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A technique is described for studying nuclear reactions in which short range alpha-particles are produced with a yield that is too small for the direct application of the electrostatic deflector. In preliminary experiments a strong polonium source is used to supply alpha-particles to the deflector, and a group of these alphas, homogeneous in energy, passes through the deflector and enters a variable pressure absorption cell and ionization chamber. Cut-off pressures determined for various alpha-particle energies result in a calibrated cell which can then be used to determine the alpha-particle energies in nuclear disintegrations. Application of this method to $Li^6(p,\alpha)He^3$ results in a Q value of 3.94 ± 0.08 Mev. The calibration, extending in alpha-particle energy from 1 to 1.8 Mev, is also used to determine the slope of the range energy curve. The average value of the slope found for this region is 200 kv per mm range.

THE direct measurement of the energies of short range disintegration particles by deflection in an electrostatic field, introduced by Allison[1] and his group, is suitable for high yield reactions. For the study of reactions in which short range alpha-particles are produced, but where the yield is too small to apply the electrostatic deflector directly, the following technique has been devised. A variable pressure absorption cell, suitable for the particles, can be calibrated by using alpha-particles from a strong natural source. These particles are slowed down in air and then allowed to pass through the electrostatic deflector which measures their energies. This cell can then be used to determine the energies of short range alpha-particles, since the solid angle through which the cell will accept particles is much greater than that of the deflector.

This paper describes such a calibration and the application of the method to the alpha-particles from the disintegration of Li^6 by protons. The latter part of the paper shows how this calibration can be used to determine the slope of the range energy curve for alpha-particles in the energy region 1–1.8 Mev.

APPARATUS

The electrostatic deflector and its accompanying high voltage source have been described in previous papers[1,2] from this laboratory. The entrance slit to the deflector was 3 mm wide and 1.3 cm high, and was located 8.9 cm (the focal distance) from the edges of the cylindrical plates of the deflecting electrostatic field. These plates were spaced 0.635 cm apart and had an average radius of curvature of 25.400 cm. They subtended an angle of 90 degrees at their center of curvature and were 8.26 cm high. A collodion foil of 1.5 cm stopping power was placed over the entrance slit to seal up this end of the deflector.

A strong polonium source[3] deposited on silver, with cross section the same as that of the entrance slit, was mounted on a screw arrangement in front of the entrance slit. Movement of the source with respect to the slit changed the portion of the range of the alpha-particles expended in air.

Figure 1 shows the arrangement of the variable pressure absorption cell and ionization chamber which the particles entered after passing through the electrostatic deflector. The opening to the absorption cell, B, 3 mm by 2 cm, served as the exit slit of the electrostatic deflector. Over B was soldered a metal screen, 0.15 mm thick, with about 650 holes per square cm, each hole being about 0.2 mm in diameter. The screen was covered on the higher pressure side by a collodion window with an air equivalent of about 1.7 mm. The brass disk containing the opening B was seated accurately against shoulders on the cylin-

[1] S. K. Allison, L. S. Skaggs, and N. M. Smith, Jr., Phys. Rev. **54**, 171 (1938).
[2] L. S. Skaggs, Phys. Rev. **56**, 24 (1939).

[3] The author is indebted to Miss M. R. Jones of the Chemistry Department for preparing the strong RaD solution used.

drical body of the absorption cell. It was held in place by a collar and sealed by a rubber gasket. The construction was such that the length of the cell was independent of the tightness with which the screws were drawn up to make the seal. The opening A, 6 mm by 2.3 cm, was covered with a similar metal screen but with no collodion film. Thus the pressures in the ionization chamber and absorption cell were the same. The absorption cell had a measured depth of about 0.59 cm and the ionization chamber of about 0.45 cm. The collection voltage of 530 volts for the ionization chamber was applied to the outside brass case as indicated in the figure. The air admitted into the cell was freed of moisture and carbon dioxide by passage through tubes of calcium chloride and sodium hydroxide. Its temperature was measured by a thermometer whose bulb rested on the cell. The pressure was measured in an open tube mercury manometer. A correction was made for the temperature of the mercury. A volume of several liters was placed on the line to stabilize the pressure.

The linear amplifier used in this work was of the resistance-coupled type with a 954 acorn pentode in the first stage. The output of the amplifier was fed into a scale-of-sixteen circuit similar to that described by Stevenson and Getting.[4]

For the study of the Li^6 reaction the high voltage set used was the Cockcroft-Walton circuit described by Hatch.[5] The arrangement of the target chamber and absorption cell-ionization chamber unit was similar to that used in a previous study[6] of this reaction in this laboratory.

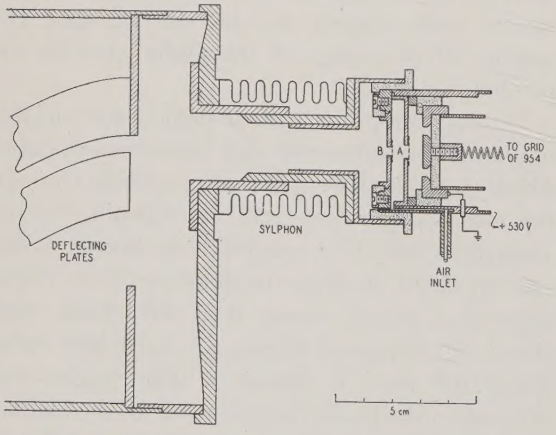

FIG. 1. Arrangement of the absorption cell and ionization chamber for taking number *vs.* pressure curves of particles which have passed through the electrostatic deflector. A pair of brass rods (not shown) keeps the sylphon extended when the deflector is evacuated.

CALIBRATION OF THE ABSORPTION CELL WITH THE ELECTROSTATIC DEFLECTOR

The performance of the variable pressure ionization chamber has been described in a previous communication from this laboratory.[6] In our work the bias on the counting circuit for the main calibration curve was 13 volts, and in a manner to be described later it was determined that a particle must produce about 4100 ion pairs in the ionization chamber in order to be counted. There is a critical operating pressure P_c above which the penetration into the chamber (in terms of air equivalent at standard conditions) required to produce a count should, theoretically, be independent of the pressure. P_c is the pressure at which the particle can produce the number of ions necessary for a count before it reaches the end of the chamber. The reason for the independence of pressure can be briefly stated as follows. The actual length of path of a particle before it loses its ionizing power is inversely proportional to the pressure whereas the specific ionization is directly proportional to the pressure.

The formula for the range of a particle as measured by the cell can be written

$$R=(L/76)(288P/T)+C, \qquad (1)$$

where L is the length of the absorption cell, T the absolute temperature and P the pressure. The first term represents that part of the range expended in the absorption cell, reduced to the standard conditions of 76 cm Hg pressure and 15°C. C represents the air equivalent of the collodion window, assumed to be constant, plus that of the penetration into the ionization chamber. This latter part, then, is also constant so long as the pressure is above P_c, which can be calculated from

$$N_0=\int_0^{D_c} I(x)dx.$$

Here N_0 is the number of ion pairs required to

[4] E. C. Stevenson and I. A. Getting, Rev. Sci. Inst. **8**, 414 (1937).

[5] G. T. Hatch, Phys. Rev. **54**, 165 (1938).

[6] G. J. Perlow, Phys. Rev. **58**, 218 (1940).

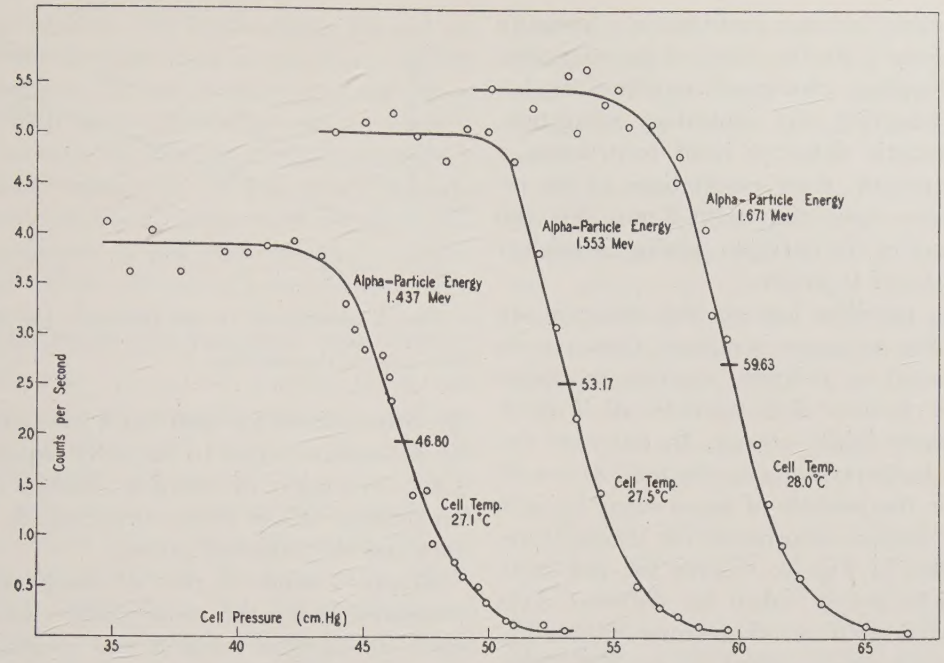

FIG. 2. Curves for determining cut-off pressure as a function of the energy of the alpha-particles.

produce a count, and is equal to 4100 for a 13-volt bias; $I(x)$ is the specific ionization function; $D_c = DP_c/76$ where D is the linear depth of the ionization chamber. If we use the curve of Holloway and Livingston[7] to represent the function $I(x)$ we find that $P_c = 27.0$ cm Hg. For this calculation the maximum ordinate of the specific ionization curve has been set at 60,000 ion pairs per cm. Only those number-pressure curves which did not start to drop off until the cell pressure was above 27.0 cm Hg were used in this work.

The quantity N_0 was determined in the following way. A thin polonium source was placed so that its alpha-particles passed through the absorption compartment and entered the ionization chamber near the end of their range. The pressure was then lowered until rough observations with the oscilloscope and counting circuit indicated that the particles traversing the ionization compartment were producing approximately the critical number of ion pairs corresponding to the selected bias. With the pressure held at this value, the distance of the polonium source was readjusted until the pulses showed a maximum height. Then an accurate measurement of the cut-off bias was made by counting at this pressure and varying the bias to get a number bias curve. Such curves were taken at various pressures. Let the pressure associated with a given cut-off bias be P_0. If the linear depth of the ionization chamber is D, then its equivalent depth at P_0 is $D_0 = P_0 D/76$. The critical number of ion pairs N_0 corresponding to a given bias may then be found from

$$N_0 = \left[\int_{\alpha}^{\alpha+D_0} I(x)dx\right]_{\max},$$

where α is to be chosen to give the greatest value for the integral.

Figure 2 shows a set of curves taken with the electrostatic deflector. Each curve was taken at a fixed voltage on the deflector plates, with the ordinates giving counts per second and abscissae the pressure in the cell as read off the manometer. The energy of the alpha-particles passing through the deflector is given[1] by $E = 40.00V$ where V is the deflecting potential in volts. An end effect correction[8] equal to $-0.0093E$ must be added on to E. The dispersion is seen to be quite high,

[7] M. G. Holloway and M. S. Livingston, Phys. Rev. **54**, 18 (1938).

[8] S. K. Allison, L. S. Skaggs and N. M. Smith, Jr., Phys. Rev. **57**, 550 (1940).

a 100-kv energy change resulting in a pressure change of about 5 cm Hg. Most of the straggling is range straggling, with small contributions due to noise straggling and ionization straggling. The electrostatic deflector itself contributes a negligible amount, since calculations of its resolving power show[1] that with 3-mm slits the energy spread of the particles passing through it is of the order of 1 percent.

Since the particles leaving the deflector are essentially homogeneous in energy, these curves can be treated as ordinary number *vs.* range curves for a group of alpha-particles all of which have the same initial energy. In our case the pressure at half-maximum can be used as cut-off pressure for the particle of mean range in each group; the values, uncorrected for temperature, are indicated in Fig. 2. Curves for the same alpha-particle energy taken on different days showed variations in cut-off pressures, amounting in the extreme case to about 1.8 cm Hg. These variations were attributed to such factors as changes in the gain of the amplifier or in the constants of the scaling circuit.

Sets of curves were taken on eight different days. On all but two of these days one of the curves was for an alpha-particle energy equal to 1.437 Mev. The average value of 288 P/T, where P is the cut-off pressure and T the absolute temperature, for these curves was 44.72 cm Hg. On the assumption that the gain of the amplifier, constants of the scaling circuit, etc., might be different on different days but essentially constant during the course of one day's runs, all cut-off pressures for the 1.437-Mev curves were adjusted to 44.72 cm Hg, and the pressures for the other curves for each day's runs were shifted by an amount equal to the shift required in the 1.437-Mev curve of that day. Table I shows the unadjusted values when corrected for temperature and the adjusted values.

TABLE I. *Values of (288/T)P for various alpha-particle energies.*

α-Particle Energy (Mev)	Unadjusted Values of (288/T)P (cm Hg)	Adjusted Values
1.730	60.62	60.68
1.671	57.13	56.79
1.553	51.10, 51.05	50.42, 50.71
1.496	47.11*	47.50*
1.437	44.24,* 44.27, 45.40 45.06, 44.79, 44.06	44.72
1.379	40.74*	41.22*
1.333	37.51*, 39.31, 39.37	37.99*, 39.76, 38.69
1.205	33.62, 34.04, 33.62	34.07, 34.07, 32.94
1.086	28.65	28.68

* Old 954 tube.

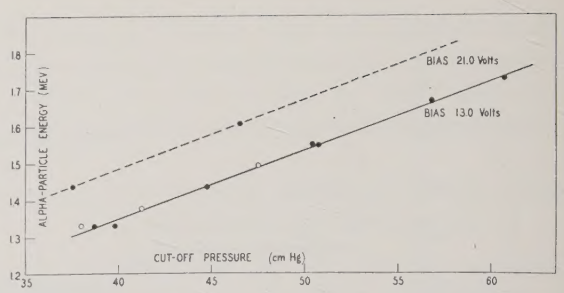

FIG. 3. Energy *vs.* cut-off pressure. The open circles represent points determined with the old 954 tube in the first stage of the amplifier.

Figure 3 shows a plot of energy *vs.* cut-off pressures. After the three points indicated by open circles were taken it was necessary to replace the 954 tube in the first stage. At this point the gain of the amplifier was adjusted so that the cut-off pressure for 1.437 Mev occurred at about the same point as with the old tube. No changes in the amplifier or in any other parts of the circuits were necessary after this. An examination of the cut-off pressures shows that the curve of Fig. 3 would not be altered essentially if the unadjusted points were used.

Use of Cell for Study of $Li^6(p,\alpha)He^3$

The absorption cell-ionization chamber device was placed opposite a thin target of lithium fluoride to detect the alpha-particles at right angles to the incident proton beam. The auxiliary apparatus, such as the amplifier and scaling circuit, was the same as that used in the calibration experiments. Moreover, care was taken to keep unchanged all the wiring connecting various circuits together, such as the leads from the output of the amplifier to the scaling circuit, etc., since changes in these might affect the operation of the circuits.

A metal disk with a 3-mm hole in the center was placed over the absorption cell slit; this opening and the target spot (5.4-mm diameter) served as the limiting aperture widths with a separation between them of 4.0 cm. The proton beam of about 5 microamperes was fed into a

current integrator. The bombarding voltage was 342 kv. This is rather close to the observed 330-kv resonance in F^{19}, but comparison of the curves obtained with those obtained in a previous study[6] of this reaction in this laboratory, made at a bombarding voltage of 370 kv, shows that the alpha-particles from fluorine were avoided. The curves obtained at 370 kv, which is farther above the 330-kv resonance, gave the same ratio of counts on the plateau to counts on the base line as that shown in our curves.

In order that the cut-off pressure should fall within the pressure range for which the cell was calibrated it was found necessary to raise the bias to 21.0 volts. Figure 4 shows a plot of the number of counts *vs.* pressure, the number of counts per point being about 220 on the plateau. The base line represents the long range alphas from Li^7 in addition to the He^3 particles and background noise. Though the points are somewhat scattered, the pressure at half-maximum is fairly well defined at 58.5 cm Hg. When corrected for temperature (28.9°C) this becomes 56.0 cm Hg.

In order to determine the energy corresponding to 56.0 cm Hg at 21.0-volt bias it was necessary to take more data with the electrostatic deflector. The energy *vs.* cut-off pressure curve at this higher bias should be parallel to the one at the lower bias, since it is only the value of C in Eq. (1) that is changed. To check this, two points were determined at the 21.0-volt bias, one with an alpha-particle energy equal to 1.437 Mev, the other 1.612 Mev. These are plotted in Fig. 3. It is seen that the line they determine is parallel to the 13.0-volt bias line. A check was also made at this time at the 13.0-volt bias, and a value of $288P/T$ of 44.03 was found for an energy of 1.437 Mev, which agrees within experimental error with the main curve. From Fig. 3 it is seen that at the higher bias a cut-off pressure of 56.0 cm Hg corresponds to an alpha-particle energy of 1.79 Mev. This gives a Q value for the reaction of 3.94 ± 0.08 Mev, the greatest part of the error resulting from the uncertainty in the cut-off pressure.

The result is in excellent agreement with the other[6] determination of this Q value reported from this laboratory. As pointed out in the report of the previous work this value gives greater consistency with various series of reactions than the previously accepted value, and can be used with other well-established Q values and masses to give a He^3 mass of 3.01688 ± 0.00011 mass units.

The present determination is independent of the slope of the range-energy curve and of the length of the absorption cell. Moreover, it does not depend on the Q value of the reaction $Be^9(p,\alpha)Li^6$ as does the previous determination. In a sense, then, the present work can be considered as a check on the beryllium reaction.

Application to Alpha-Particle Range-Energy Curve

The data of Table I can be used with Eq. (1) to give information about the alpha-particle range energy curve in this region. If L and C were known the curve could be determined absolutely. If only L is known the data can be used to give the slope of the range-energy curve. In those experiments[6] where energies are determined by comparison with particles of known energy, only the slope of the range-energy curve need be used.

In determining the proper value of L to use in the case where the pressure in the ionization chamber is variable, one is confronted with such unknown factors as the point at which the collecting field of the ionization chamber be-

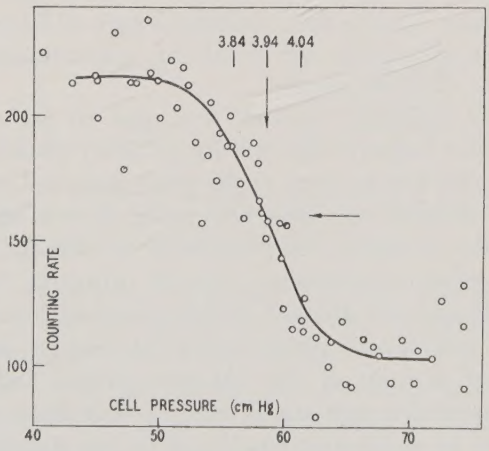

FIG. 4. Counts *vs.* pressure for alpha-particles from Li^6 (p, α) He^3. The base line represents the He^3 particles and the long range alphas from Li^7, plus the background. The horizontal arrow indicates the half-maximum. The lines and numbers at the top indicate where the half-maximum would have to occur to give the various Q values.

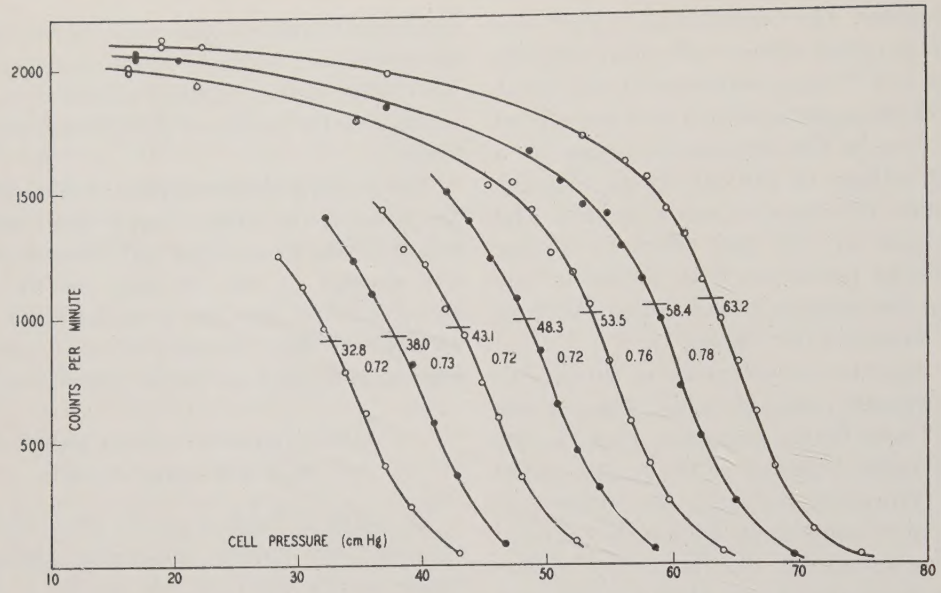

FIG. 5. Determination of the effective length of the absorption cell. The figures between the curves are the computed values of the cell length using adjacent curves. The other figures are cut-off pressures (pressures at half-maximum). Locations of plateaus for the four curves at the lower pressures were determined by solid angle calculations. An average value of effective cell length of 0.740 cm is indicated, with some evidence for a variation in cell length of about 3 percent over region of pressures used.

comes effective and the constancy of that point. In addition the variation in the recombination of ions at different pressures may be significant for such a device. There are also the usual uncertainties in determining the length of a short absorption cell such as the irregularities of the screens and the protruding of the collodion window through the screen apertures. Because of all these factors, the measured length (0.59 cm) of the absorption cell is only an approximation to the effective length.

The following method[6] was used to get the effective length of the cell. An auxiliary chamber was attached in front of the absorption cell and this chamber was kept evacuated. It was thus possible to reduce the pressure in the absorption cell below atmospheric without rupturing the absorption cell window. A thin polonium source, mounted on an accurate metric micrometer, was placed in front of this chamber (which had a front circular opening of one-half inch diameter sealed by a collodion window of 13-mm stopping power) along the axis of the absorption cell-ionization chamber device. A number-pressure curve was taken for a given position of the source. With a cut-off pressure of P at temperature T the range of the particles is given by

$$R=x(p/76)(288/T)+L(P/76)(288/T)+C, \quad (2)$$

where x is the length of path of the particles in air and p is the atmospheric pressure. For another position of the source, that is, for another value of x, we get another equation for R, since the range of the particles is the same. If C is assumed to be constant, the two equations can be solved for L. If p and T do not change between any two curves the value of L is independent of the absolute values of x but depends only on the difference of the x values, which can be accurately read on the micrometer. If p and T do change, the absolute values of x enter only in a small correction term.

Preliminary sets of such curves gave an average value of L of 0.74 cm. Since the discrepancy with the measured value was large the cell length determinations were repeated with a collodion film on the screen between the absorption cell and ionization chamber. This made it possible to keep the ionization-chamber pressure constant at atmospheric so that the device was being used in the conventional way. Two determinations were made under these conditions.

The values obtained were 0.61 cm and 0.60 cm, in good agreement with the measured length of 0.59 cm. These results were taken as evidence that with no window between the two compartments, part of the ionization chamber was effectively part of the absorption cell. Though the entire explanation for this is not known, it seems clear that the correct length to use for the electrostatic deflection experiments, in which the window was not present, is 0.74 cm.

A final set of curves to determine the cell length without a film on the ionization-chamber opening was taken. In these experiments the alpha-particle source on the micrometer screw was moved only one-half mm between curves, in an attempt to find out if the effective cell length varied with pressure. A study of this variation requires the use of curves whose cut-off pressures are close together. A difference in position of the alpha-particle source of one-half mm gives a difference in cut-off pressures of about 5 cm Hg. However, if one uses two such curves to compute the effective cell length, an error in the difference of cut-off pressures of only 3 mm would result in a 6 percent error in the cell length, that is, an error of about 0.04 cm. Since the difference in cut-off pressures for any two positions of the micrometer source is reproducible to within about 3 mm, this method can determine the variation of cell length to an accuracy of about 6 percent.

The set of curves is plotted in Fig. 5. The locations of the plateaus for the four curves at the lower pressures could not be determined experimentally, as they would occur at pressures much below the critical pressure P_c mentioned above, and the ionization chamber would not record all of the particles. These plateaus can, however, be calculated from solid angle considerations, since the number of counts on the plateaus for these experiments changes only because of the change in the solid angle which the opening to the absorption cell subtends at the source. The three plateaus that were determined experimentally checked these calculations. Though some of the points on these plateaus were taken at pressures slightly below P_c, the general appearance of the curves makes it certain that practically all of the counts were being recorded. The gradual decrease from the plateaus which the curves of Fig. 5 exhibit is characteristic of number-distance curves for ordinary thin sources. The effect appears exaggerated in Fig. 5 because of the scale used for abscissae; 10 cm Hg correspond to only about 1 mm distance in air at standard conditions.

The figure between any two curves indicates the cell length computed by using those curves. The average value of 0.74 cm for the cell length over the range of pressures used is substantiated. If the cell length is calculated by using the difference in cut-off pressures between the curve at the highest pressure and that at the lowest pressure, a 3-mm error in this pressure difference results in only a 1 percent error in cell length, that is, an error of less than 0.01 cm. This, then, is a measure of the accuracy with which the average effective cell length is known.

Though the accuracy with which this method can determine the variation in cell length is not high, there does seem to be an indication in Fig. 5 of a downward trend in the effective cell length as the pressure is lowered. A variation in this direction of about 3 percent for the range of pressures used in the electrostatic analyzer data was assumed. The data in Table I was

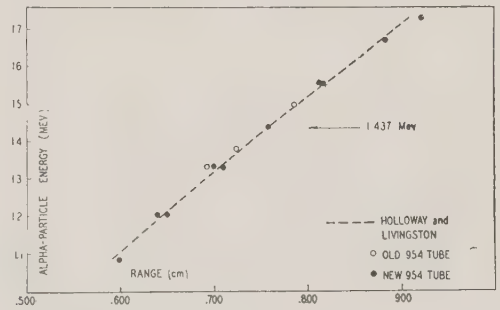

FIG. 6. Points on the range-energy curve in the region studied. The data were matched to the Cornell curve of Holloway and Livingston at 1.437-Mev energy.

used as follows. For pressures greater than 55 cm Hg L was set equal to 0.750 cm, for pressures between 35 and 55 cm a value of 0.740 cm was used for L, and for the two lowest pressures a value of 0.730 cm. An absolute range of 0.758 cm was assigned to the 1.437-Mev alphas, as determined from the latest Cornell[7] curve. This gives C a value of 0.323 cm. The results are plotted in Fig. 6. The points are seen to agree well with the curve of Holloway and Livingston. The spread

of the points is not serious, since the dispersion of the method is so high that the greatest spread corresponds to less than ± 0.01 cm in range. The chief uncertainty is in the value of L used. The results can be said to give an average value of the slope of the range-energy curve in this region of 200 kv per mm range to within 3 percent. This result is independent of the assumption made by Holloway and Livingston (who obtained the range-energy curve in this region by integrating their specific ionization curve) that the ratio between energy loss by ionization and by excitation is constant. Our result, then, is an indication of the validity of this assumption for this region.

The author is greatly indebted to Professor S. K. Allison for his very helpful supervision of this research. He wishes to thank also Dr. L. S. Skaggs and Dr. N. M. Smith, Jr., for their help in performing the experiments.

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